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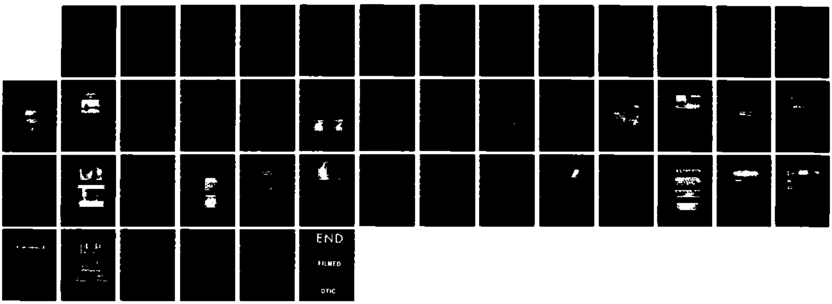

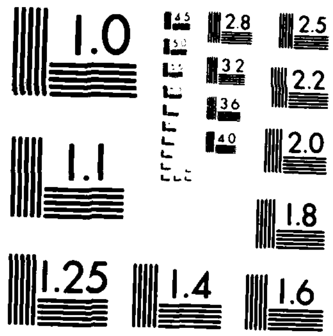

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Report MM & T 1073

MANUFACTURING METHODS AND TECHNOLOGY FOR REAL-TIME ULTRASONIC IMAGING

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30 JUNE 1982

FINAL REPORT ON TASK I FOR PERIOD 1 OCTOBER 1981 – 30 JUNE 1982

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The breadboard of a real-time ultrasonic imaging system was constructed and demonstrated. The core of the breadboard RTUIS was a liquid surface holographic inspection system to which a number of digital features were added to give video monitoring, 3-D presentations of flaws, frame summing, decision making on defects, contrast enhancement, filtering and smoothing. RTUIS demonstrated its capability to locate flaws in composite and metallic structures ranging from thin graphite epoxy rings, to Viper launch tubes, to Viper rocket motor casings, to thick (5-inch) stainless steel weldments.		

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SUMMARY

This report describes work done on Contract No. DAAH01-81-D-A030, Task I to assemble a real-time ultrasonic imaging system (RTUIS) in breadboard form and to demonstrate its potential for production line nondestructive inspection of fiber laminate or metallic structures. In the course of this work, the RTUIS breadboard was assembled and demonstrated using a selection of production line components. Included in the breadboard assembly were a basic real-time ultrasonic imager, manipulators for handling cylindrical and flat objects, a special slit camera, and a selection of video image processing equipment. Salient features of the ultrasonic imager were its speed and compatibility with video image processing systems. The imager has the capability of providing over 200 full frame images per second, each containing over 4,000 resolvable picture elements, all picture elements being acquired in parallel in 100 microseconds. During the demonstration, the imager operated at 60 frames per second. A video camera, focused upon a liquid surface detector plane, generated the initial unprocessed video image signal.

Five pieces of video image processing equipment that provided for frame averaging, video signal analysis, threshold detection, and x, y, z isometric display using the brightness level as the z-dimension were used.

A special slit camera was designed and built to demonstrate the anticipated benefits of digital frame averaging that are to be implemented through the use of a scrolling digital image memory when the RTUIS prototype version is built. This camera performed video image summing and provided instant hard copy records of the ultrasonic image. Manipulators, which carried objects through the field of view in a manner compatible with the operation of the slit camera, were demonstrated.

Among the production components used in demonstrating the imaging characteristics of the breadboard system were Viper launch tubes, Viper rocket motor casings, Tomahawk cruise missile aluminum squeeze castings, and heavy austenitic steel weldments. Pictures included in this report give a sampling of the results.

A1

PREFACE

General Dynamics Convair Division is pleased to submit this copy of the Final Report for Task I, Build Breadboard Real-Time Ultrasonic Imaging System, under Contract No. DAAH01-81-D-A030 with the U.S. Army Missile Command entitled "Manufacturing Methods and Technology for Real-Time Ultrasonic Imaging," for work done in the period October 1, 1981 to June 30, 1982.

General Dynamics teamed with Battelle-Pacific Northwest Laboratories in Richland, Washington to create the breadboard of a real-time ultrasonic inspection system that has the potential of inspecting a Viper launch tube in one minute or less.

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SECTION 1

INTRODUCTION

BACKGROUND

The evaluation of the quality of a production line item is an essential and significant part of the production process. Often the factors affecting quality can only be detected using radiation that passes through the material of which the part is made. The most common forms of penetrating radiation are x-rays and ultrasound, although beams of particles such as neutrons can be used for some inspection tasks. Gamma rays, especially those generated by the radioactive decay of Cobalt 60, are used in the inspection of large metallic structures. An ultrasonic inspection method is often chosen to avoid radiation hazards associated with x-rays and nuclear particles. More often, an ultrasonic method is chosen because it is uniquely effective for detecting the type of defect that is likely to occur. Delaminations in layered structures may be used as an example. A delimination represents a very distinct and sharp discontinuity and is a strong barrier for the transmission of ultrasound, but unless seen edgewise, is usually undetectable by x-ray or other methods of nondestructive testing using ionizing radiation.

Standard production line ultrasonic testing methods use a transducer that scans the item, generating an echo whenever a void volume or inclusion is encountered in the otherwise uniform volume of the piece being examined. This approach requires a simple geometry and does not provide an image of the part being examined. In order to provide an image, specialized scan techniques have been developed that generate either a cross-sectional view (B-scan) or a plan view (C-scan) of the piece. These specialized scan methods are normally too slow to permit 100 percent inspection in production line situations. They build up an image a point at a time or, at most, a line at a time.

In order to establish more advanced inspection techniques and technology, the U.S. Army Missile Command (MICOM) issued a request to develop a real-time ultrasonic imaging inspection system that will detect critical flaws in welded and composite structures. The RFP divided the effort into two tasks. Task I is to establish component requirements and qualitatively determine the flaw detection reliability of the ultrasonic system. Task II will define, design, and prepare test specimens to verify system developed during Task I and provide an industry wide demonstration.

The work done under Task I is reported in this document.

THE PROBLEM

With the increasing complexity of structural design and the usage of advanced materials, a need exists for better inspection techniques and technology. Conventional ultrasonic inspection techniques may be grouped into two categories: nonimaging and imaging. Typical limitations of the nonimaging (A-scan) techniques are that they do not characterize the flaw adequately. They yield only a one-dimensional representation of the flaw. Typical limitations of the conventional B-scan and C-scan techniques are that they are slow. They do not generate a real-time image. Images are built up point-by-point or line-by-line and not area-by-area. Implementation of rapid automatic flaw detection and defect decision logic would be difficult if not impossible using these old established techniques.

SOLUTION TO THE PROBLEM

The solution to the problem as conceived by General Dynamics and Battelle combines a number of new and old ideas into a viable package. One of the new ideas uses the blinding speed of present day microprocessors to create a real-time environment for the inspection system. Their speeds can be used to digitize video images, then to eliminate or greatly reduce the background noise while enhancing the contrast between the defect and its neighboring vicinity by integrating the defect's image over a number of image frames. Another idea uses an isometric projection to give a 3-dimensional appearance to the flaw in a video display. The x and y directions give the cross-sectional region containing the flaw. The z direction gives the magnitude of the distortion of the impinging ultrasonic energy at the flaw, caused by either absorption or reflection. The other major idea adapts an existing liquid surface inspection system that creates the flaw's image by means of acoustical holography.

TECHNICAL APPROACH

Our technical approach is to acquire the necessary microprocessors and digital electronics hardware and integrate them into the existing liquid surface inspection system. Table 1 summarizes the elements of the conceived real-time ultrasonic imaging system (RTUIS) and indicates whether these elements already exist and can be incorporated as is, whether they exist but need modification, or whether they are new elements to be added to the system. The imaging tanks, optical beam control prisms, and spatial filter already exist in workable form but we know they can be redesigned to realize significant operational improvement.

The manner in which these basic elements will be created and integrated into one functioning RTUIS system is shown in Figure 1. The existing liquid surface inspection system provides the mainframe, lenses, prisms, light source, and basic video equipment. It also includes the electronic control and sequence timer, but this circuitry will be modified to operate at a higher pulse rate. The

Table 1. Element Summary of the RTUIS

RTUIS System Elements	Existing	Modification	New
Mainframe	X		
Electronic control & sequence timer		X	
Imaging tank		X	
Collimating lens	X		
Pulsed light source	X		
Imaging lens	X		
Optical beam control prisms		X	
Spatial filter		X	
Video camera	X		
Real-time video monitor	X		
Integrated display monitor			X
Digital image processor			X
Video tape recorder	X		
Hard copy printer			X
Mechanical scanner			X

existing imaging tank will be replaced with one that responds uniformly to a broader range of ultrasonic frequencies and is more stable against corrosion, temperature changes, and fluid level. Similarly, the optical beam control prisms and spatial filter will be redesigned for firm stable operation in a production environment.

The result of these improvements to the existing system is an improved basic system. Other elements must be added to this improved basic system to achieve the operating capability of the RTUIS. Two of these, the hard copy printer and the integrated display monitor, are purchased items. The digital image processor and the mechanical scanner must be designed and fabricated. Both of them will be designed to create flat, rolled-out images of cylindrical objects. Other shapes can also be imaged in the system but each type of object requires specific insonification arrangements such as frequency, pulse width, pulse delay, adjustment of acoustic lenses, design of ultrasonic transducer, etc. The image flattening feature included in the digital image processor will be switched out when noncylindrical objects are being imaged.

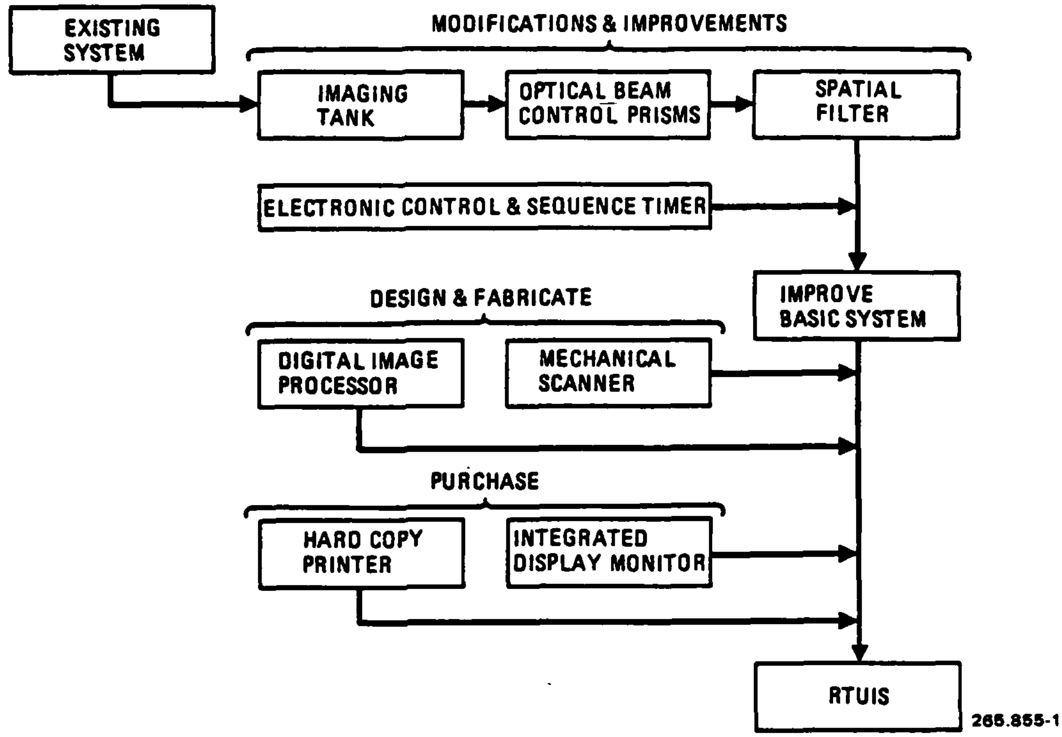

Figure 1. RTUIS Flow Diagram

In order to develop the RTUIS in an orderly fashion, we will first build a breadboard RTUIS composed of all the necessary elements of the final RTUIS but it will not be an integrated system. It will consist of electronic boxes and microprocessors that we rent or borrow and tie into the basic liquid surface inspection. It will perform all the functions of the final RTUIS or, in some cases, simulate the final effect expected out of a specific function. In this way, we can demonstrate the capability of the final RTUIS early without making a large financial commitment. Then, if something goes wrong, or doesn't meet our expectations, we can expose the weak spot and invent our way around it.

The second phase in the development of the final RTUIS is to use the knowledge gained in the breadboard RTUIS to design a truly integrated functional inspection system. This will be followed by the purchase of components and subsystems, their integration, assembly, and test. When we have completed the second phase, we will have developed a production-oriented prototype of RTUIS. It will be demonstrated in a production environment.

SECTION 2

HOLOGRAPHIC IMAGES FROM THE LIQUID SURFACE INSPECTION SYSTEM

To show why we think the liquid surface inspection system is a good choice to be the fundamental building block in RTUIS, we present several pictures of flaws and the scanning technique that permits digitization and reconstruction of the flaw's image from the intermediate hologram. These pictures do not include any video signal processing. They are the direct output from the basic liquid surface inspection system.

A composite block with holes drilled in one end ranging from 0.5 mm to 3.0 mm in diameter is shown in Figure 2a. The ultrasonic image in Figure 2b clearly shows the depth each hole was drilled.

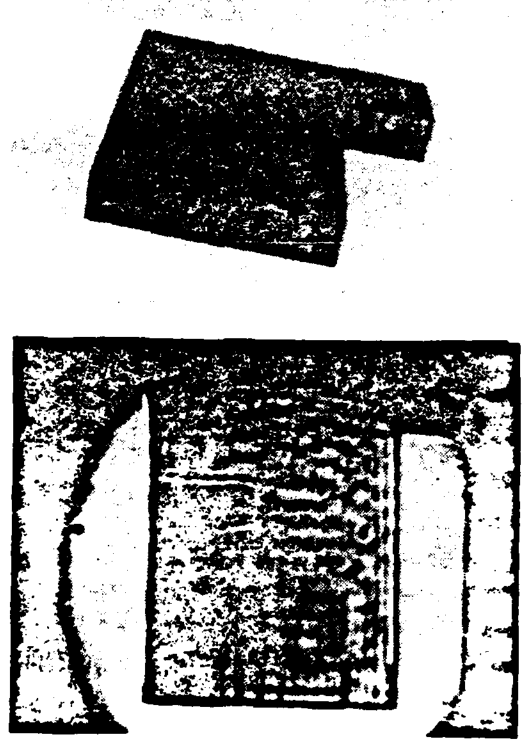

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Figure 2. Composite Block and Its Ultrasonic Image (5 MHz)

Figure 3 shows a steel cylinder with wall thickness of 0.125 inch and a hole drilled lengthwise into the shell with a 0.120-inch diameter. The imaging was done at 3 MHz to reveal the depth of the drilled hole.

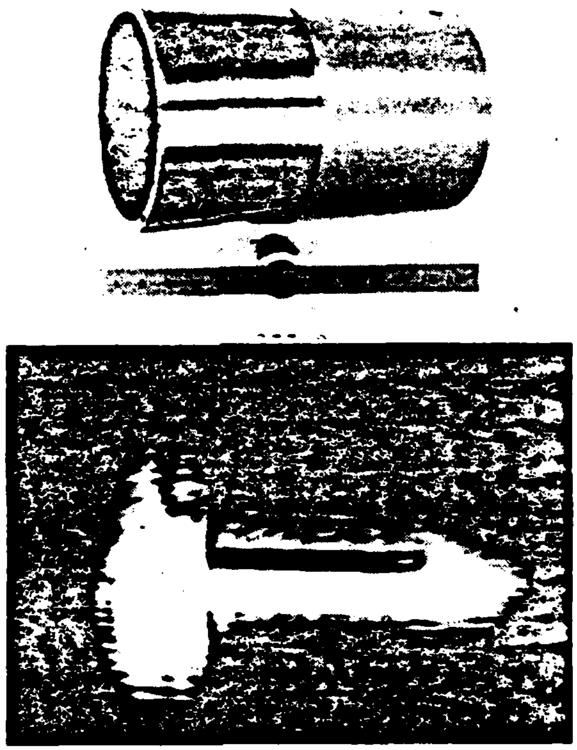

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Figure 3. Ultrasonic Image of a Hole Drilled in a Steel Cylinder

Acoustical holography has been demonstrated, both theoretically and in practice, to have the highest resolution of any acoustic instrumentation available. Acoustical holographic systems are a factor of two or higher in resolution than any other imaging device because of their simultaneous source-receiving scanning capability.

ANALYSIS OF SCANNED ACOUSTIC HOLOGRAPHY

For any inspeciton system, it is important to obtain the highest resolution possible. The lateral resolution (Δx) in object space is defined as the distance that the object point can be moved sideways before the number of fringes in the hologram change by 1, or its equivalent, a phase change of 2π occurs.

The phase at the receiving transducer in the hologram plane during the recording process is

$$\phi\ (x,y,z) = \frac{2\pi}{\lambda_s}\left[r_o' + r_1' - r_2'\right] \tag{1}$$

The hologram geometry and symbols are shown in Figure 4.

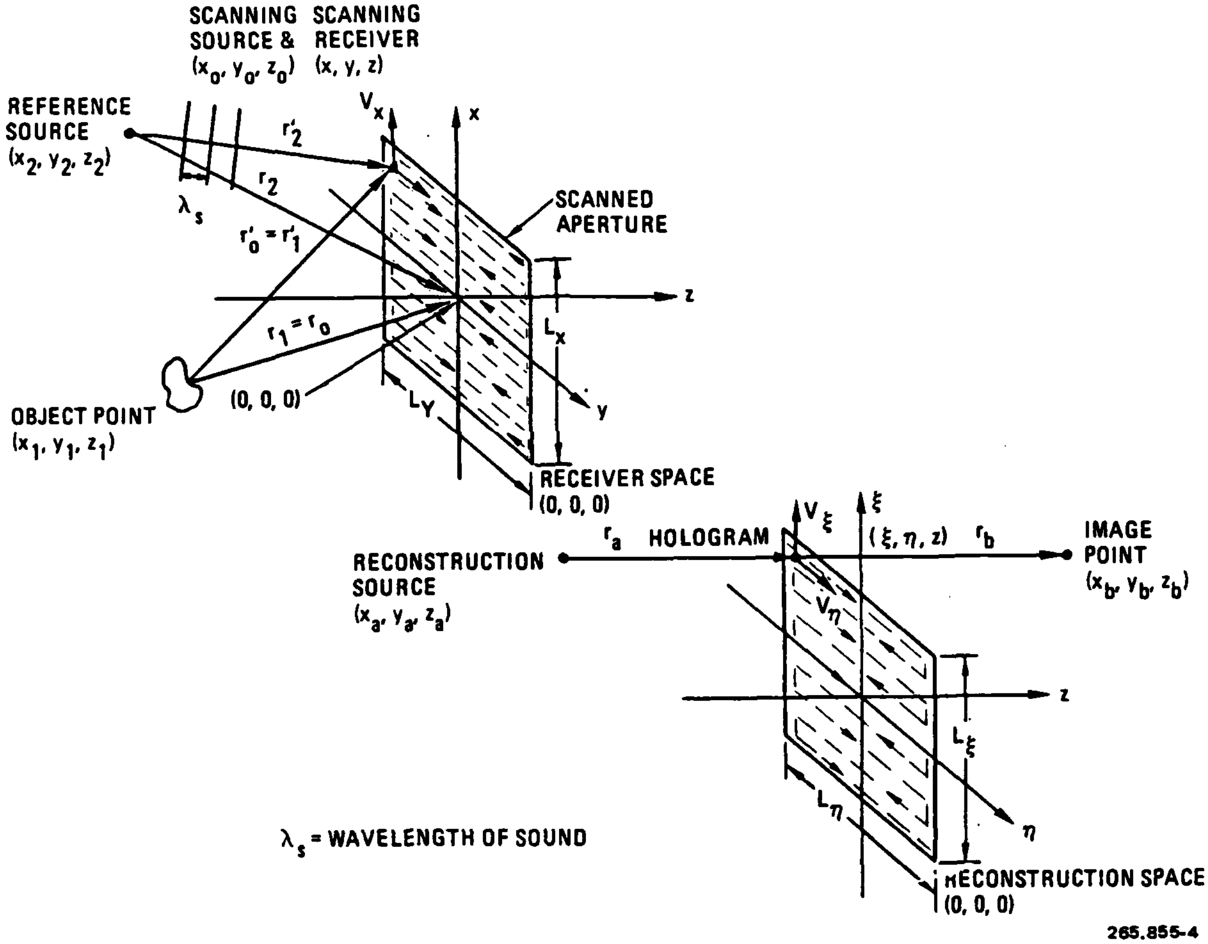

Figure 4. Geometry for Scanned Acoustic Holography

If the object distances are large compared with the aperture dimensions, then the distance terms can be expanded in a binomial series with retention up to the second order terms. Equation (1) can then be expressed as:

$$\phi\,(x,y,z) \cong \frac{2\pi}{\lambda_s}\left[r_o + r_1 + r_2 + \frac{x^2}{2}\left(\frac{1}{r_1} + \frac{1}{r_o} - \frac{1}{r_2}\right) - x\left(\frac{x_o}{r_o} + \frac{x_1}{r_1} - \frac{x_2}{r_2}\right)\right] \tag{2}$$

where we consider only the x-z plane.

The phase at the aperture extremes are:

$$\phi\ (x = + L/2) \cong$$

$$\frac{2\pi}{\lambda_s}\left[r_o + r_1 + r_2 + \frac{L^2}{4}\left(\frac{1}{r_1} + \frac{1}{r_o} + \frac{1}{r_2}\right) - \frac{L}{2}\right.$$

$$\left.\left(\frac{x_o}{r_o} + \frac{x_1}{r_1} - \frac{x_2}{r_2}\right)\right] \tag{3}$$

and

$$\phi\ (x = - L/2) \cong$$

$$\frac{2\pi}{\lambda_s}\left[r_o + r_1 + r_2 + \frac{L^2}{4}\left(\frac{1}{r_1} + \frac{1}{r_o} - \frac{1}{r_2}\right) + \frac{L}{2}\right.$$

$$\left.\left(\frac{x_o}{r_o} + \frac{x_1}{r_1} - \frac{x_2}{r_2}\right)\right] \tag{4}$$

The phase difference between the aperture extreme is:

$$\phi = \frac{2\pi}{\lambda_s} L\left(\frac{x_o}{r_o} + \frac{x_1}{r_1} - \frac{x_2}{r_2}\right) \tag{5}$$

The incremental phase change, as a function of the incremental change in the lateral object position, is given by the following expression:

$$\Delta\phi = \frac{2\pi}{\lambda_s}\ \frac{L}{r_1}\ \Delta x_1 \tag{6}$$

The final result for the lateral hologram resolution (stationary source) is then:

$$\Delta x_1 = \lambda_s\left(\frac{r_1}{L}\right) \tag{7}$$

and for simultaneous source-receive scanned holograms,

$$\Delta x_{1_s} = \lambda_s\ \frac{r_1}{2L} \tag{8}$$

The longitudinal or depth resolution is more difficult to define mathematically than the lateral resolution. The longitudinal resolution, as stated by Hildebrand, can be related to a decrease in intensity of the image as a result of an incremental change in r_b. The object point can then be moved an incremental distance r_1 to achieve the same decrease in intensity of the image. The longitudinal resolution can then be expressed as:

$$\Delta r_1 \cong \lambda_s \left(\frac{r_1}{L}\right)^2 \tag{9}$$

Equation (7) is the lateral image resolution if we employ either a stationary point source or receiver. The resolution is increased by a factor of two if both the point source and receiver are simultaneously scanned. This, of course, is the normal procedure for synthetic aperture radar.

RESOLUTION WITH LONGITUDINAL AND SHEAR WAVE ILLUMINATION

Acoustical holography imaging techniques have been extremely successful using longitudinal and shear-wave illumination to image flaws deep within metallic sections. The following results have been included to briefly review some of the basic resolution capabilities in both longitudinal (L) and transverse or shear (S) wave holography.

Figure 5 shows a "Y" pattern geometry with respect to an aluminum block. One branch of the "Y" contains holes separated edge-to-edge at the resolution limit of 2 mm at 2.6 MHz. The hole separation of the other two branches are 4 mm and 8 mm respectively. The three-dimensional drawing indicates the observer's view of the holes with longitudinal-wave illumination.

The hologram and reconstruction image is shown in Figure 5b. The image shows the 2 mm separated holes are resolvable, but very close to merging together. The hole separations at 4 mm and 8 mm are easily resolvable in the two right-side branches.

An example of shear-wave resolution is shown in Figure 6. Seven flat-topped holes are drilled on the diagonal block surface. The holes are 6.4 mm in diameter and placed in a "Y" pattern. The hole spacing in the first row is 2 mm edge-to-edge; second row is 3 mm edge-to-edge, and third row is 4 mm edge-to-edge. The reconstructed image resolves the 2-mm edge-to-edge holes.

KEY SYSTEM REQUIREMENTS

Certain key features were specified for incorporation into the new advanced real-time ultrasonic imaging system. It was specified that the system should include the following capabilities:

a. Produce a real-time video image/printout.

b. Capability of contrast enhancement/flaw detection in real time.

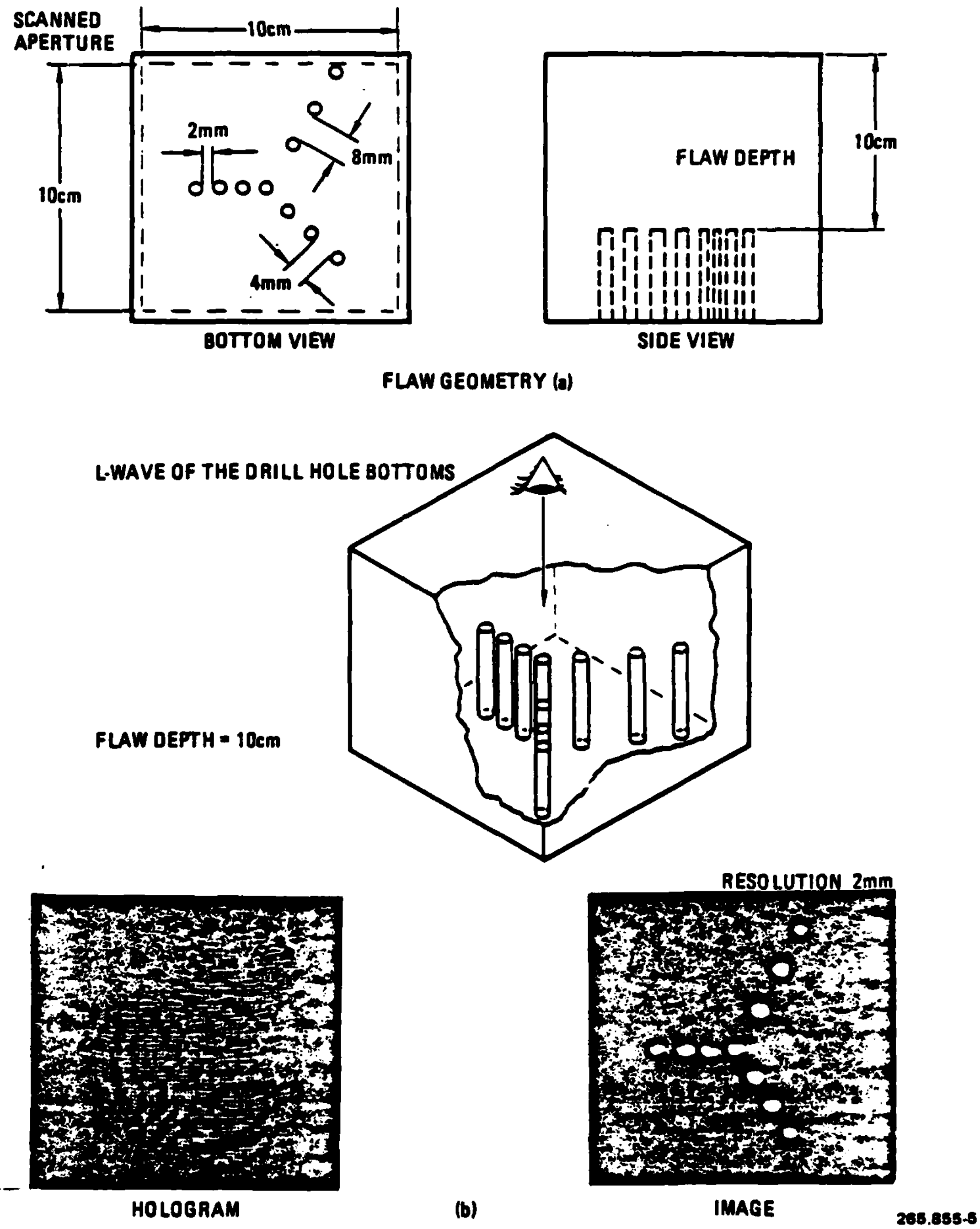

Figure 5. Longitudinal-Wave Resolution Geometry Hologram and the Reconstructed Image (2.6 MHz)

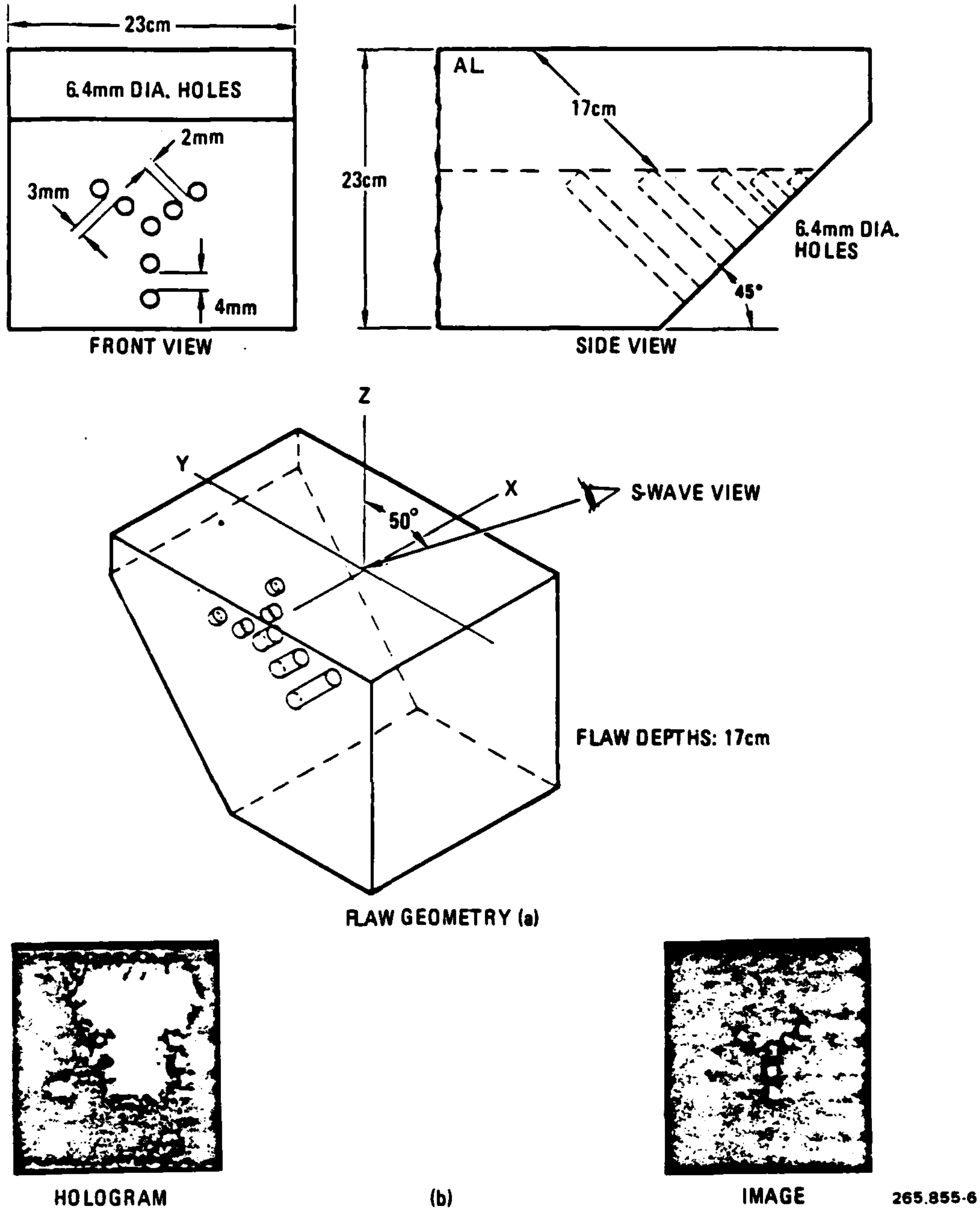

Figure 6. Shear-Wave Resolution Geometry Hologram and the Reconstructed Image (3 MHz)

c. Capability of pattern recognition/defect decision language.

d. Quantitative measurements of defects shall be simple and rapid.

e. Inspect complex geometries.

f. Summing frames to reduce signal noise in semireal time.

g. Filtering and smoothing to improve flaw recognition.

h. Storing image on magnetic tapes for retrievable processing or reinspection.

i. Capable of presenting a full three-dimensional image of the defect regions instantaneously.

j. System shall be production oriented.

BREADBOARD REAL-TIME ULTRASONIC IMAGING SYSTEM

Battelle has many years of experience in applying ultrasonics to nondestructive examination of industrial and military components. Included in this experience is the development of unique imaging systems based upon the principles of isometric display and the principles of ultrasonic holography. Several types of ultrasonic holography systems have been worked with extensively. The type most suited to meet the requirements of the Manufacturing Methods and Techniques for Real-Time Ultrasonic Imaging uses a liquid surface as a detector of ultrasound and as the interface between ultrasound and light. A schematic diagram of this system is shown in Figure 7. Sound generated by the object transducer interacts with the object. The interaction encodes information about the object on the ultrasonic wave, which, therefore, is sometimes called the object wave or object beam. Characteristics of the object are encoded into the ultrasonic wave by absorption, refraction, diffraction, and reflection. Lenses L1 and L2 image the object into a liquid surface detector. Disturbances in the object tank caused by moving the object are prevented from propagating to the liquid surface hologram by a Mylar window. A reflector turns the axis of the beam 90° and directs it to a small tank having a thin plastic bottom through which the ultrasonic beam propagates to the surface of the thin layer of liquid. Ultrasound from the object beam reaching this surface is mixed with ultrasound from a reference transducer to create a liquid surface diffraction grating or hologram. In order to read out this hologram, it must be illuminated with collimated light from a coherent source. Light from a pulsed argon ion laser is focused and then expanded to fill the aperture of a collimating lens mounted above the liquid surface hologram. The light is diffracted and reflected by the grating impressed upon the liquid surface by the interfering ultrasonic beams. A collimating lens focuses the reflected light in the plane of the spatial filter where only first order diffracted light is transmitted to the video camera. The video camera is focused on the liquid surface as seen through the collimating lens. The end result is that the object is seen on the video monitor.

The system shown in Figure 8 is uniquely suited to serve as the starting point for the advanced real-time ultrasonic imaging system (RTUIS). It has an object field of up to five inches in diameter. Normally the system is adjusted to image a 2.75 × 3.5-inch field with resolution into 4,000 picture elements (linear resolution of 0.040 inch). The system forms a complete picture of this field in 10^{-4} seconds. Allowing five milliseconds delay time between pictures, the system can deliver 200 pictures per second. This high rate of image formation is the salient feature of this system.

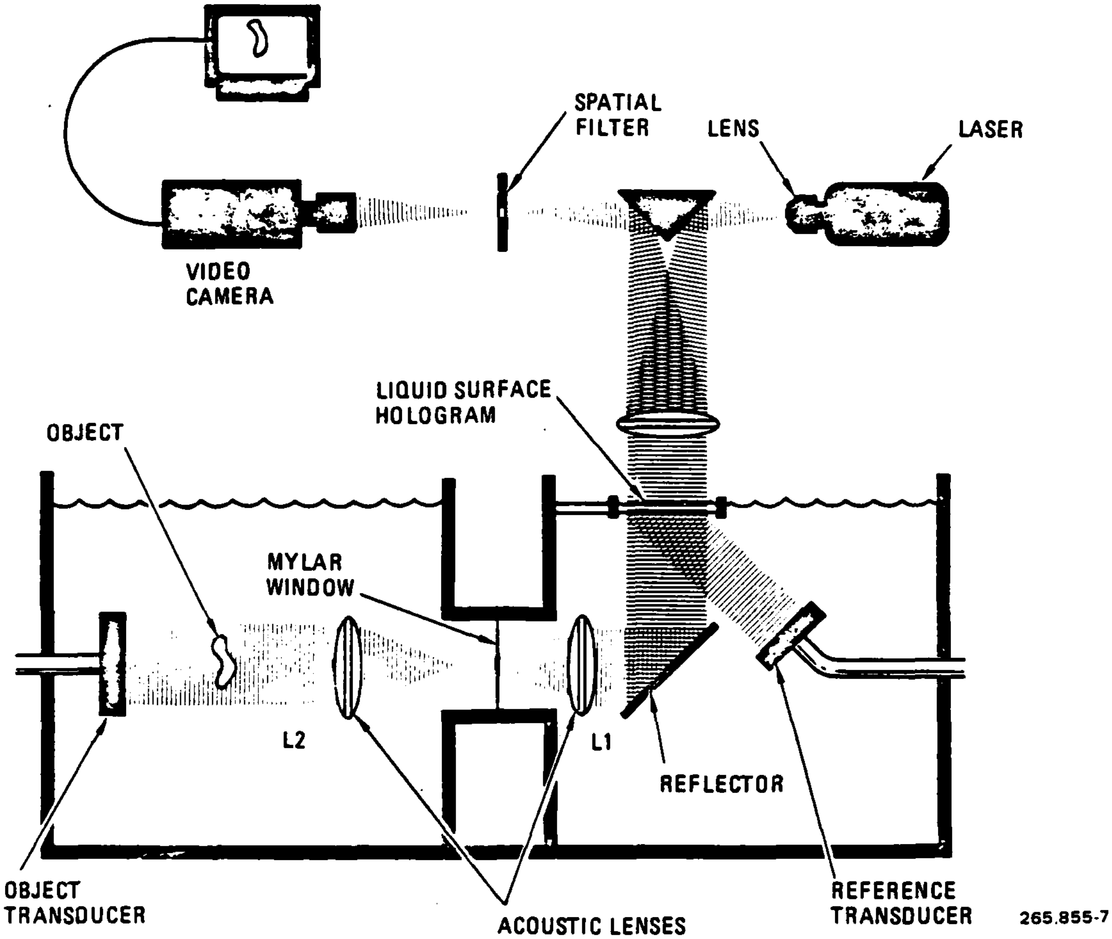

Figure 7. Schematic Drawing of the Basic Real-Time Ultrasonic Imaging System

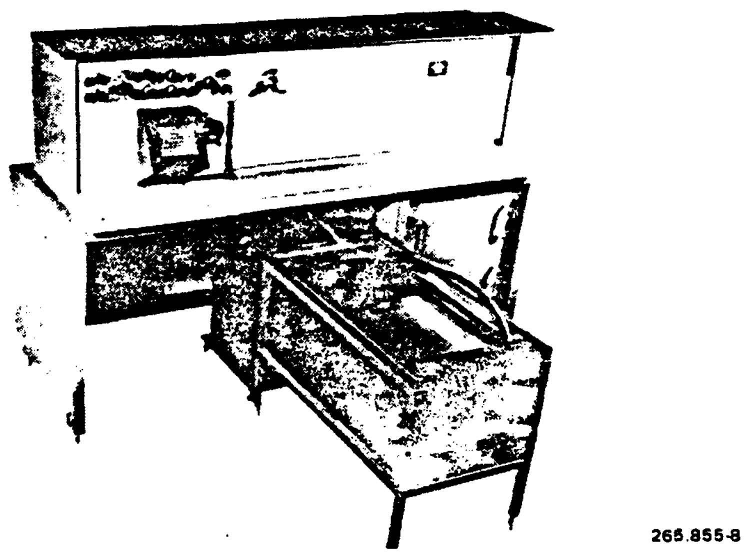

Figure 8. Basic Real-Time Ultrasonic Imaging System

During the course of our effort in Task I, the basic system was improved in several ways in order to properly evaluate and demonstrate its inspection capabilities. The video camera was remounted to give greater image stability and a noninverted image. The spatial filter assembly was reworked to provide greater ease of adjustment. Ultrasonic reflectors were built to facilitate inspection of rotating tubular objects. A slit camera was built to demonstrate the memory scrolling technique of background noise reduction. Manipulators and adaptors were built to handle rotating cylinders and to translate plates through the field of view.

In addition to these changes, several pieces of video image processing equipment were incorporated into the system. The complete system used in the laboratory demonstration is illustrated in Figure 9. The items on the right side of the figure are components of the basic ultrasonic imaging system. The new video image processing equipment added is shown on the left. These new equipment items include the slit camera, video monitor, image processor, video analyzer, video detector, isometric processor, x,y,z display, a second video monitor (processed image monitor), a hard copy printer, and a video cassette recorder.

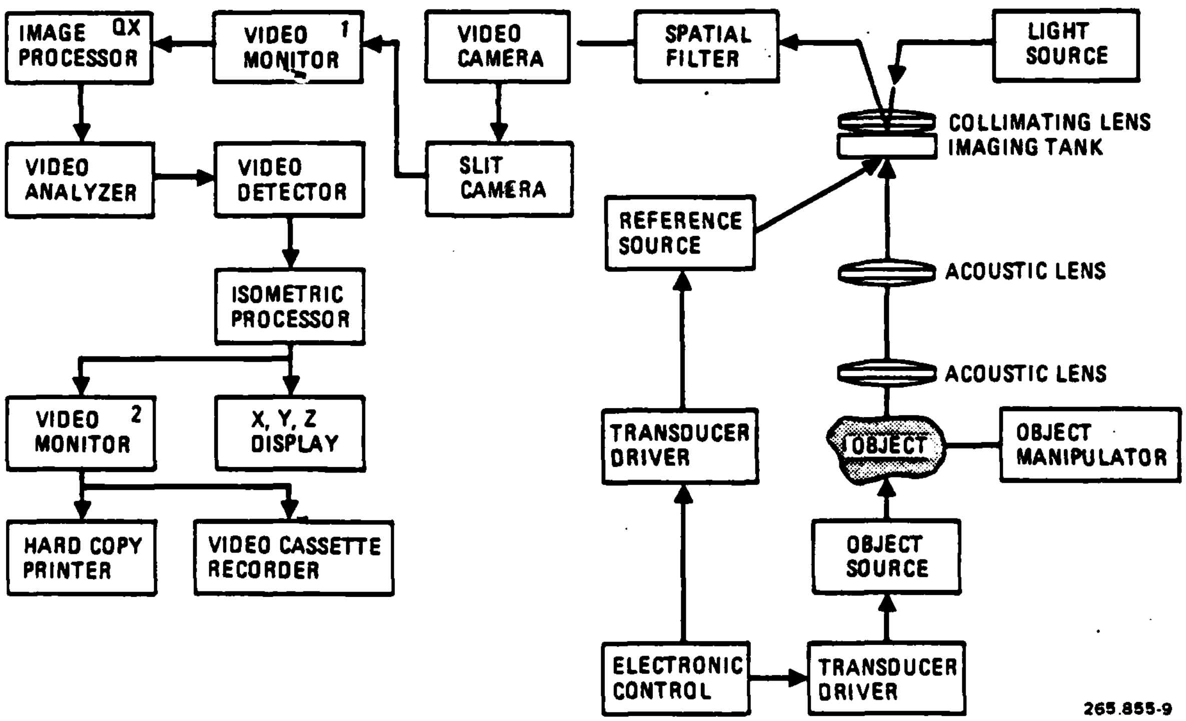

Figure 9. Block Diagram of the RTUIS Breadboard

Figure 10 is a picture of the RTUIS breadboard built up during Task I. An aluminum squeeze casting from a Tomahawk cruise missile is mounted in the object manipulator to the right of the chair. Images of this object are shown in the video monitors. For cylindrical objects such as the Viper launch tubes, a different manipulator was used that rotated the object on a vertical axis. A better view of the video image processing equipment is given in Figure 11. The various components from top to bottom on the left side are the x,y,z display, the isometric processor, the real-time digital image processor, and the processed image monitor. Void volumes in an aluminum squeeze casting are seen in the image on the monitors. On the right side at the top are two video monitors, one for the unprocessed and one for the processed image. Below the monitors are the video detector and the video analyzer. At the bottom is the slit camera.

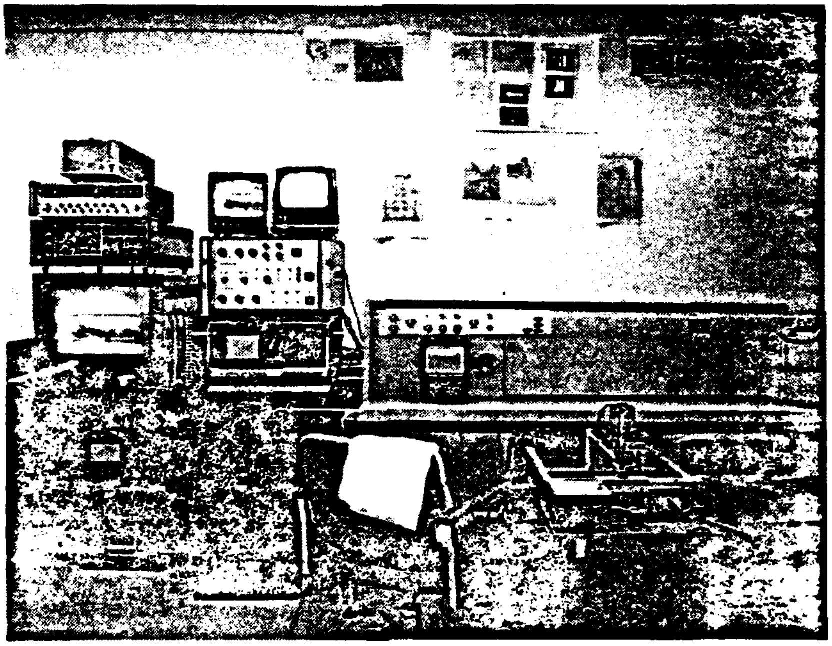

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Figure 10. RTUIS Breadboard Imaging an Aluminum Casting

The functions that these systems perform are discussed in the following paragraphs.

DESCRIPTION OF VIDEO IMAGE PROCESSING EQUIPMENT

The video image processing equipment referred to in Figure 9 will be discussed in the order in which the video signal is dealt with, starting with the slit camera.

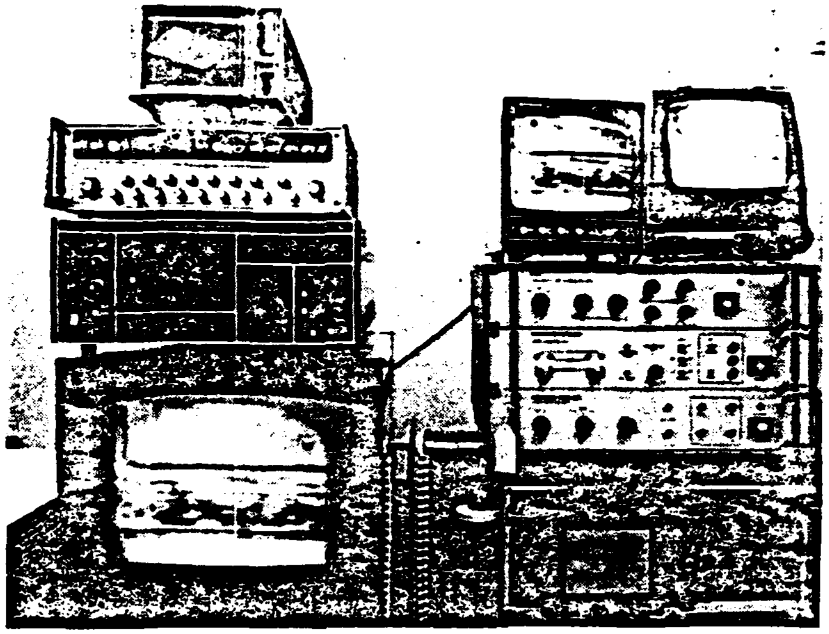

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Figure 11. Video Image Processing Equipment Used in the RTUIS Breadboard Demonstration

Slit Camera

The slit camera was built to record objects moving across the field of view of the ultrasonic imager at a uniform rate. It consists of a camera lens mounted in a dark enclosure as illustrated in Figure 12. At one end of the enclosure there is a small rectangular opening past which the film moves as a picture is being taken. The film is driven along a track at a speed that matches that of the image formed by the camera lens. A video monitor is positioned at the other end of the enclosure. The image on this monitor is relayed at 0.4 × magnification to the film plane by the lens.

This camera was built for the purpose of demonstrating that the background pattern generated by the reference and object sources could be eliminated by frame summing as the object moves through the field of view. A typical background pattern is illustrated in Figure 13. It arises as a result of diffraction from the edges of the reference and object beam transducers. It is the near field pattern of these transducers. The effect of frame summing is illustrated in Figure 14. Some vertical striations remain, but the background is much more uniform than when no summing is used. This type of summing or averaging is also useful in removing coherent speckle and acoustic interference patterns in the image.

It is not intended that the slit camera will be a part of the RTUIS prototype. The camera was built to illustrate and prove what can be expected from using a scrolling digital video memory with frame summing capability. In the RTUIS prototype, the slit camera function will be implemented in digital electronics.

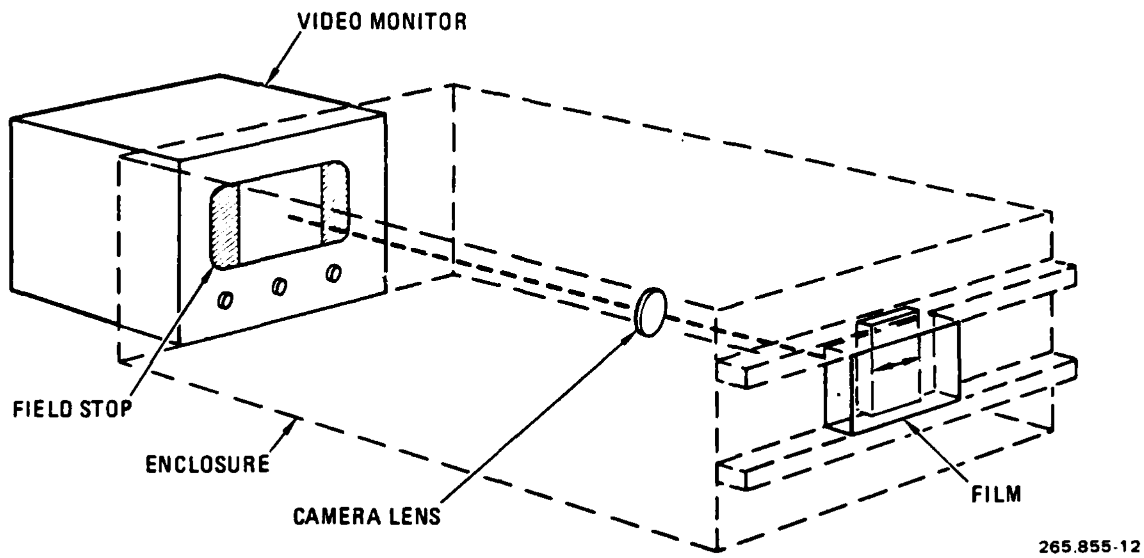

Figure 12. Slit Camera

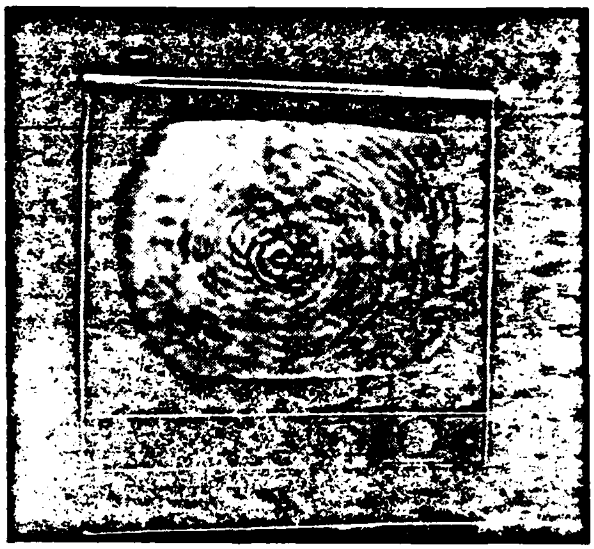

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Figure 13. Typical Background Pattern

There is an advantage to the type of image produced by the slit camera or its electronic counterpart that goes beyond the removal of background irregularities and coherent speckle effects. The resulting image integrates the effects of insonification from a continum of angles. A plane wave incident upon the inner surface of a tubular object couples with the surface over a range of angles of incidence such that the wave is converted to shear or transverse mode in the object over some of the range. The resulting picture combines the effects of these different modes of insonification to produce an improved rendering of the structures in the object.

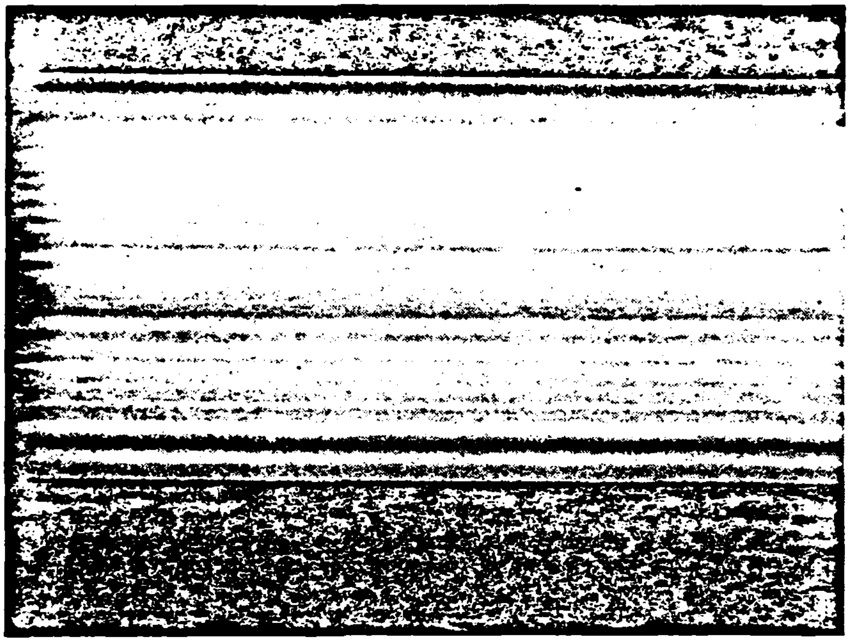

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Figure 14. Background from Frame Summing Using the Slit Camera

Video Monitor No. 1

This monitor and the video monitor in the slit camera both display the real-time, unprocessed image directly from the video camera.

Image Processor

A real-time digital image processor was used to assess the effects of frame averaging. Frame averaging to remove reference and object source diffraction (near field) patterns was implemented by oscillating the two ultrasonic sources a few degrees about an axis parallel to their surfaces while doing a 32-frame average. The ability to average any number of frames from 2 to 128 in real-time is a unique feature of this equipment and is very effective in smoothing background irregularities arising from near field patterns, coherent speckle, and interference effects.

The processor, in its present configuration, can deal only with objects that are stationary in the field for the period required to develop an 'N' frame average. That period is one-half second when N is 32 frames. A qualitative evaluation of frame averaging in this application is given in Figure 15. Background interference is reduced as the number of frames averaged is increased, but most of the improvement has occurred by the time N = 32.

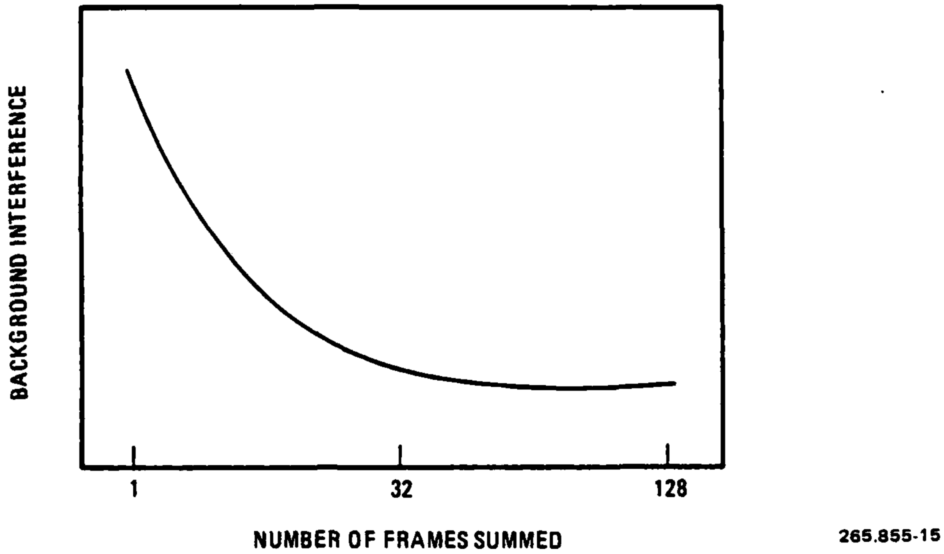

Figure 15. The Effect of Frame Summing in the Reduction of Background Interference

Ultrasonic source movement was used in the demonstration of the breadboard RTUIS. This mechanical technique will be replaced with electronic methods in the RTUIS prototype and in subsequent systems. Whenever the object can be scanned through the field of view, as with cylindrical objects such as Viper launch tubes or rocket motors or plate-like objects such as the Tomahawk cruise missile squeeze casting, the electronic equivalent of the slit camera will be used.

The electronic equivalent of the slit camera is a scrolling digital memory. By scrolling the memory while moving the object through the field of view, all background patterns are averaged to a uniform value. The effect is equivalent to frame averaging while holding the object stationary but moving the sources through the field of view. The result, which differs somewhat from that achieved by oscillating the sources, is illustrated in Figures 16 and 17. Coherent speckle and interference effects obscure true object features in Figure 16. The true object structure is more accurately revealed in Figure 17.

The real-time digital image processor has other useful features. The gray scale can be expanded or compressed. A selected span of gray levels can be amplified to full output range while all levels outside that range become black. This provides a contour of objects within the field of view. In another mode of operation, a selected scan of gray levels can be amplified to full output range while all gray levels below that range become black and all levels above that range become white.

Video images contain a massive amount of information. A standard 512 × 512 video image contains 262,144 picture elements (pixels). With a 12-bit gray scale

265.855-16

Figure 16. Image of a Flawed Area in a Viper Launch Tube as Seen Without the Benefit of Image Processing

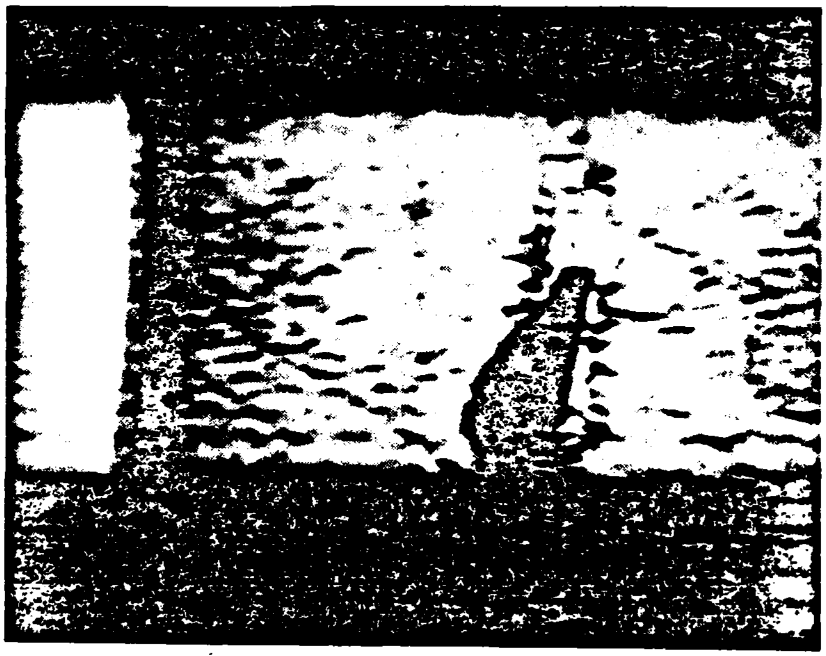

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Figure 17. Image of a Flawed Area in a Viper Launch Tube Produced by the Slit Camera Technique

resolution, a memory capacity of over 3 million bits is required. Many digital video image processing systems consist of an analog to digital (A/D) converter and a separate computer with image processing software. This configuration has three bottlenecks that would impact and impair the real-time nature of the RTUIS system. These three bottlenecks are

- Slow A/D converter
- Slow transfer between A/D converter and computer
- Slow computer software

These bottlenecks were overcome by using a stand-alone digital image processor that simultaneously inputs, computes, and outputs pixels at the rate of 10 million pixels per second. At this rate it takes only 1/30 of a second to transfer an entire picture. With these features, digital image processing becomes truly real time. Because of the manner in which the processing is carried out, the scrolling memory feature can be added for the RTUIS prototype in a manner that will enhance both the processing speed and the quality of the image.

Video Analyzer

A video analyzer was used with the RTUIS breadboard to provide an accurate measure of video output levels. Accurate knowledge of the output levels is essential for set up of automatic defect decision criteria. The video analyzer acts as a sampling scope. It displays vertically line-selected video waveforms directly on the screen of the same video monitor used to display the image. The display includes an electronic reference grating with horizontal and vertical markers which facilitate quantitative readout of video levels in easily identified regions of the image.

Video Detector

In the RTUIS breadboard a video detector was used as a defect decision device. Whenever the video signal drops below and/or rises above preset limits, this device provides an automatic warning signal. In the RTUIS prototype, a second type of defect decision device will be added. A dc voltage proportional to the integral of the video signal falling within a selectable window area will be generated. Since delaminations become dark areas in the video display, the dc voltage level will be a measure of the area of the defect. Whether or not a given defect is acceptable or unacceptable can therefore be automatically decided on the basis of the voltage level.

Isometric Processor

Gray level can be treated as a third or z-dimension, which together with the x,y,z position characterizes a video image pixel in terms of three coördinates. By rotating the coordinate system in which this type of video image is viewed, useful enhancement of the video image is obtained. The image is presented as an isometric projection on a CRT display. This display is designated as the x,y,z display in Figure 9.

In the RTUIS breadboard, the isometric processor was used in three different ways, two of which are illustrated in the following figures. The raw unprocessed image could be displayed directly upon the x,y,z monitor. This mode of use was effective in emphasizing the passage of a flawed area through the field of view, but was difficult to capture in a still shot. A second mode of use resulted from using a frame summed image such as that produced by the slit camera and displayed in Figure 18 as the input to the isometric processor. The image can then be rotated and tilted so that the delaminated region appears to be a flat topped mountain in the field of view as illustrated in Figure 19. This mode will be most effectively utilized in the RTUIS prototype where the scrolling digital memory replaces the slit camera. The processed image will then be directly available as an input to the isometric processor.

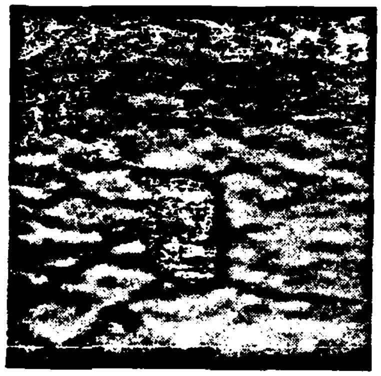

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Figure 18. Slit Camera Image Without Isometric Processor

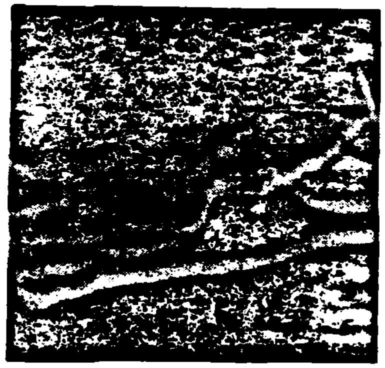

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Figure 19. Isometric Processor Image Based Upon Slit Camera Image

A third mode of operation that will also be available in the RTUIS prototype is illustrated in Figures 20 and 21. In this mode the video signal passes through the isometric processor *before* being applied to the slit camera. To be effective, only a small amount of tilt and no rotation is used in contrast to Figure 19,

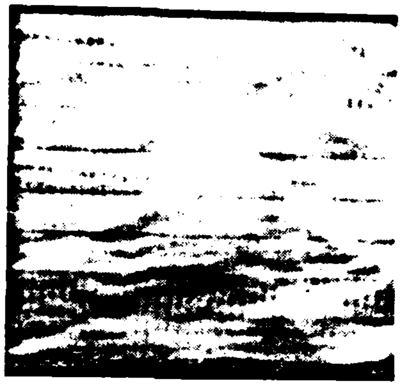

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Figure 20. Slit Camera Image with Isometric Processor, No Level Clipping

265.855-21

Figure 21. Slit Camera Image with Isometric Processor, Level Clipped

which involved large amounts of both tilt and rotation. Figure 21 differs from Figure 20 only in having a cut-off level so that the delaminated region is displayed black.

Figure 18 has left and right reversed relative to the other pictures in the set.

Video Monitor No. 2

The video monitor following the isometric processor in Figure 9 is the processed image monitor. In the RTUIS breadboard, it accepted input from one or more of the preceding subsystems and provided output to the hard copy printer and video cassette recorder. The ultrasonic image of the letter 'H' milled on an aluminum plate shown in Figure 22 was recorded using the hard copy printer.

RESOLUTION

The total number of resolvable picture elements included in an image depends upon the size of the field of view, the frequency of the ultrasonic wave and the aperture of the imaging system. The RTUIS breadboard produces a 5-inch

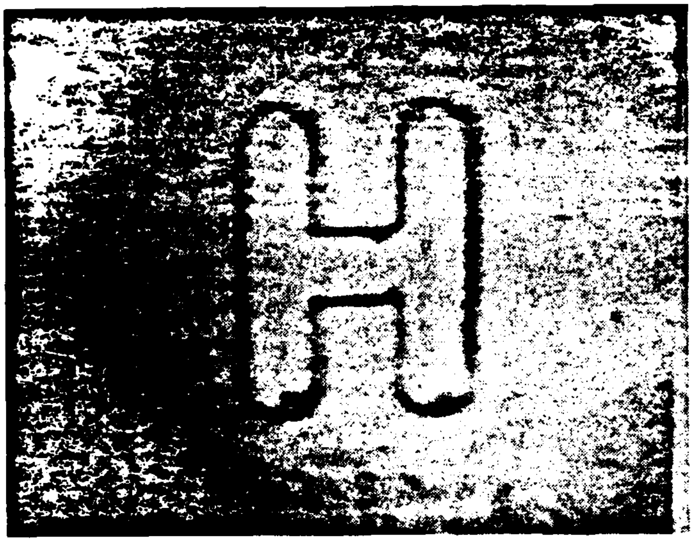

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Figure 22. Photograph of a Hard Copy Print on Dry Silver Paper by a Standard Commercial Hard Copy Printer

diameter object field, but this field is reduced to about 2.75 × 3.5 inches by the apertures of the video system. Frequency (ν) and wavelength (Λ) are related to each other through the velocity of the ultrasonic wave. Since water is most often used as the couplant between ultrasonic sources and the objects to be examined, the velocity, c, is 1.5×10^5 cm/second (5.9×10^4 in/second). The wavelength at any given frequency can be determined from $\Lambda = c/\nu$. At 5 MHz, the wavelength in water is 0.012 inch.

There are two ways of expressing the aperture of a system. It may be expressed in terms of the ratio of the diameter of the aperture to the focal length of the system. This ratio is called the f/# of the system. The other manner of expressing the aperture is in terms of the sine of the angle of the cone of rays eminating from each object point and passing through the system.

In terms of f/#, the total number, N, of resolvable points in the image is given by

$$N = \left(\frac{\nu}{c\ (f/\#)}\right)^2 A$$

where A is the area of the field of view. At ν = 5 MHz and with (f/#) = 4.15, the total number of resolvable elements is 4,000. The parameters used above are typical of the RTUIS breadboard operation.

MANIPULATORS

Manipulation of the object during frame summing is as important as any other feature in the imaging system. Objects of different basic shapes require basically different manipulators. We have built two manipulators, one suitable for long radius (6 inches = ∞) cylinders and one for short radius (1 to 6 inches) cylinders. The radius of 6 inches is a convenient but not a clear-cut dividing line between the two.

The short radius cylinder is mounted directly to the shaft of a variable speed motor, which in turn is mounted on a heavy photographic tripod as illustrated in Figure 23. The tripod adjustment feature is used for vertical positioning. Insonification is provided for by directing energy from an ultrasonic source up to the axis of the cylinder to the desired elevation and then reflecting it out in the direction of the axis of the ultrasonic imager. In Figure 23, the ultrasonic image is represented by lenses L1 and L2 and by the reflector and imaging tank.

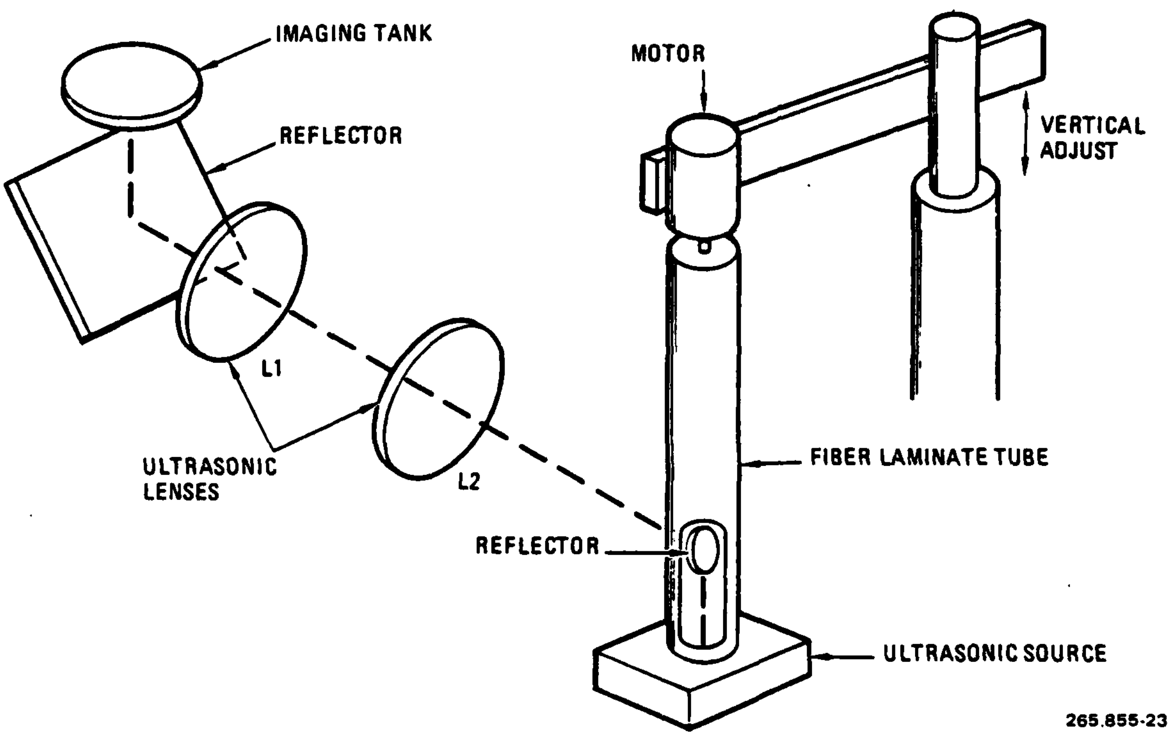


Figure 23. Manipulator for Tubular Cylindrical Objects

Long radius cylinders are handled with the manipulator shown in Figure 24 in which the object is carried along a linear track, but, as it moves along the track, it rotates. The center of rotation is located at the pivot and the position of the pivot is adjustable. A 5-inch diameter ultrasonic source is used to isonify the object. This manipulator can also be adjusted to move an object across the field without rotating it.

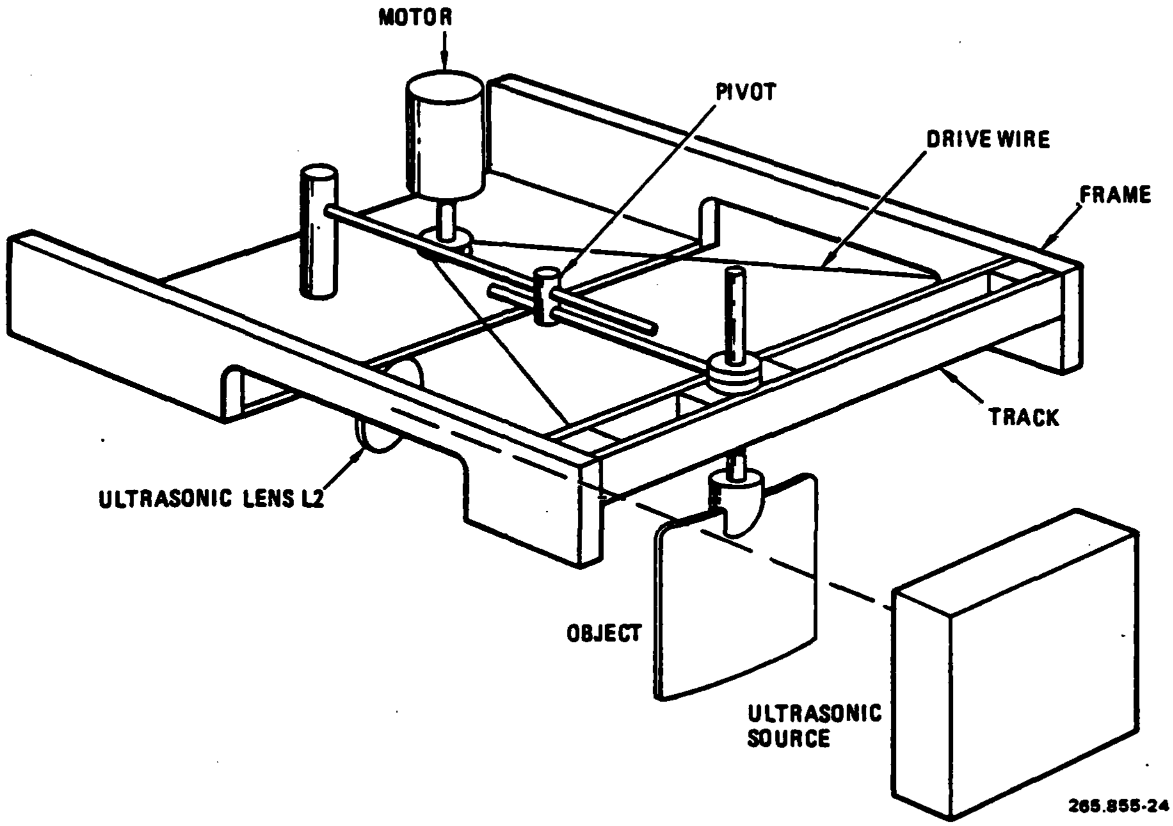


Figure 24. Manipulators for Long Radius Cylinders or Flat Objects

SECTION 3

RTUIS BREADBOARD SYSTEM PERFORMANCE EVALUATION

Evaluation of the performance of the RTUIS breadboard system was based upon its ability to image test patterns and flaws in a variety of objects including the following:

- Viper launch tubes
- Viper rocket motor casings
- Castings
- Weldments
- Aluminum, steel, and nylon plates
- Graphite epoxy structures

IMAGES OF RESOLUTION TEST PATTERNS

In order to test the resolution of the imaging system, holes were drilled in a one-half inch thick nylon plate. Two types of patterns were used as illustrated in Figures 25 and 26. In Figure 25 the holes are imaged with their axes parallel to the direction of the sound while in Figure 26 the sound path is perpendicular to the axis of the holes. Using the 'Y' pattern, the resolution is adequate to reveal that holes 0.060 inch in diameter spaced 0.060 inch apart edge-to-edge are separate and distinct.

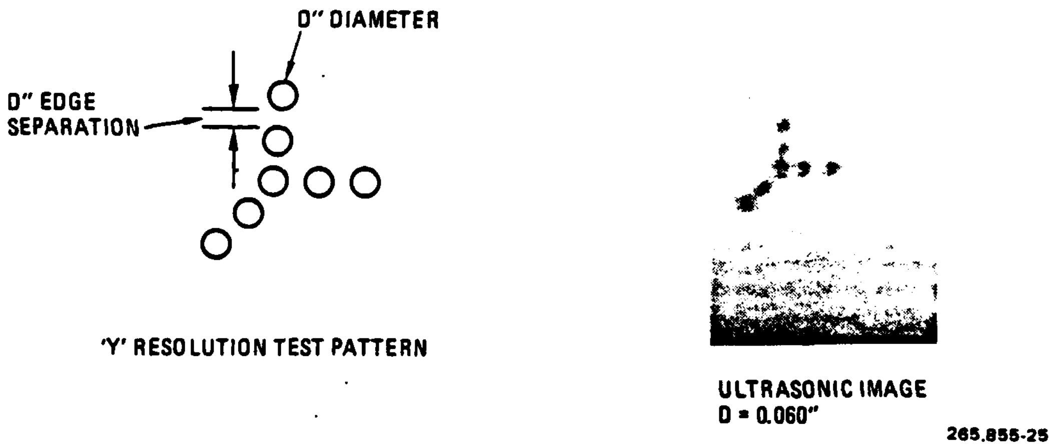


Figure 25. Resolution Test 'Y' Pattern

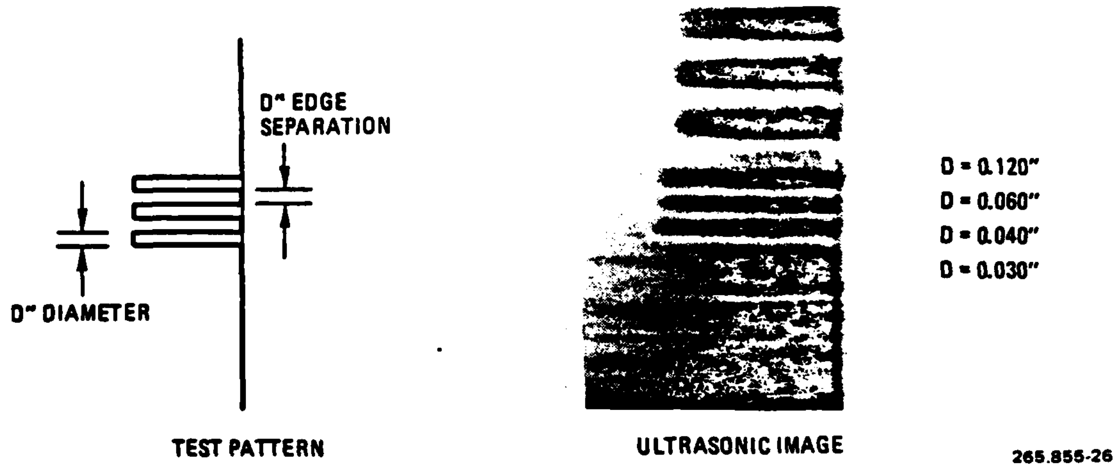


Figure 26. Resolution Test Drill Hole Triplets

In Figure 26, where the axes of the holes are perpendicular to the path of the sound, patterns with a characteristic dimension D of 0.030 inch are resolved.

IMAGES OF TEST SPECIMENS

All of the images shown here except one were produced with the ultrasonic system operating at 5-MHz frequency. The one exception is the image of the large austenitic steel block. It was imaged at 3 MHz.

Large Stainless Steel Block

Figure 27 includes an ultrasonic image (3 MHz frequency) of a 'Y' pattern viewed through 4.8 inches of austenitic steel. Each hole in the 'Y' pattern is one-eighth inch (3 mm) in diameter. Hole spacings vary from 0.137 inch for the short leg of the 'Y' to 0.216 inch for the long leg. Frame summing was essential to producing a clear picture of these holes. Approximately 30 frames were averaged while the object beam sound source was oscillated. The picture demonstrates the power of frame summing for removing coherent speckle and bringing out image detail. With no sound source wobble, coherent speckle completely obscures the 'Y' pattern. Wobbling the sound source causes the coherent speckle pattern to move about so that an average of 30 image frames produces a clean background, leaving only valid object structure in the image.

Viper Rocket Motor Casing

Figure 28 is a slit camera picture of a Viper rocket motor casing. Figure 28a records the normal structure with no defects. The rocket motor casing has a rough surface, which in itself obscures fine detail within the structure. In

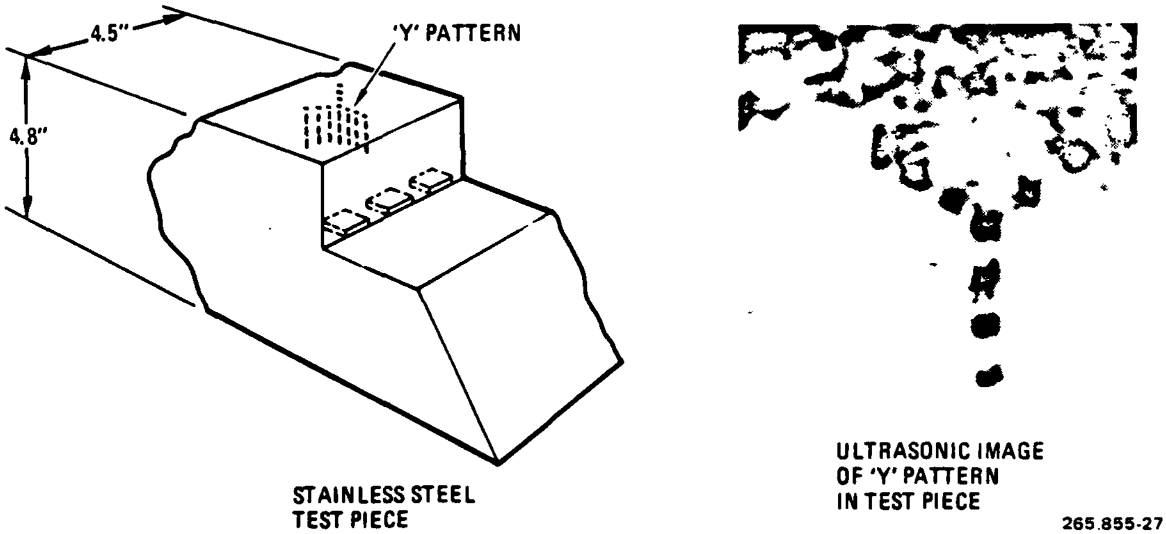


Figure 27. Ultrasonic Image of a 'Y' Pattern Drilled into a Block of Austenitic Steel

these images, the axis of the motor is vertical. The circumference has been laid out flat. Each picture records approximately half of the circumference. In Figure 28b a piece of the aluminum liner, 0.2 inch square, has been removed by grinding. The grinding extended beyond the aluminum liner into the fiber glass epoxy material. A circle identifies the ultrasonic image of this region. Presented in this manner, this flaw could easily be missed. Using gray level slicing provided by the image processor and video detector, the flawed region can be recognized as the brightest area in the image. Figure 28d was produced by feeding the level sliced image to the slit camera. The resulting picture seen on the video monitor and recorded by the slit camera leaves no doubt as to the location of the flawed area.

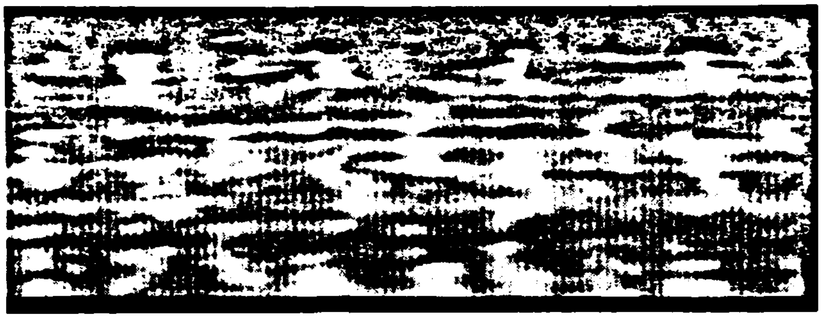
Detection of another type of flaw is illustrated in Figure 28c. Here a delamination induced by a hammer blow is clearly imaged as a dark semicircle in the lower center of the picture.

Viper Launch Tubes

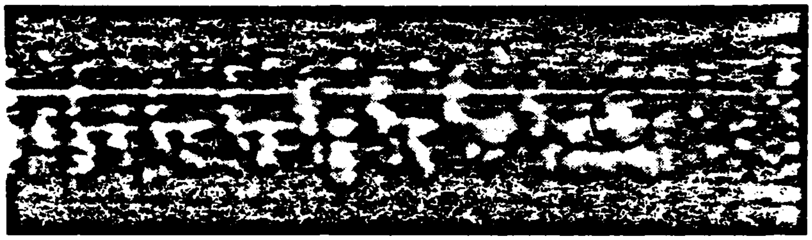
Nondestructive evaluation of the integrity of Viper launch tubes is one of the prime potential applications for RTUIS. Several examples of the ultrasonic images of these tubes produced by the RTUIS breadboard are presented here.

'H' Half Shell

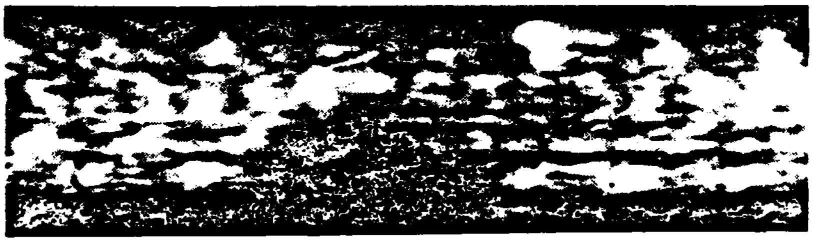
The segment of Viper launch tube shown in Figue 29 has an 'H' filed in its outer surface. In addition, there is a region over which some of the surface material has been chipped away. Underlying this chipped-off area is a delamination that



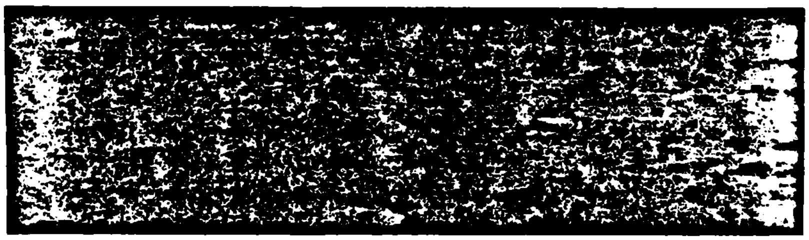
a. NORMAL – NO KNOWN DEFECTS



b. ALUMINUM LINER GROUND OUT IN A 0.2 INCH SQUARE REGION WHICH IS ENCIRCLED



c. DELAMINATED REGION IMAGED AS A DARK HALF CIRCLE



d. ENHANCED IMAGE OF THE ALUMINUM LINER FLAW SHOWN ABOVE

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Figure 28. Ultrasonic Images of a Viper Rocket Motor Casing Taken with the Slit Camera. The Circumference is Presented as a Flat Image

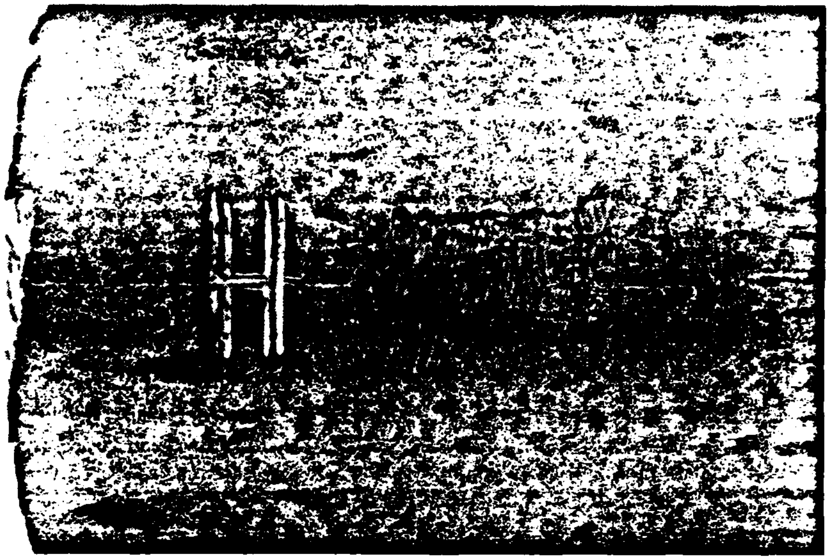

Figure 29. Photograph of 'H' Half Shell

is clearly imaged by ultrasound as shown in the frame summed image of Figure 30. Ultrasonic images of this same piece are also shown in Figures 30 and 31.

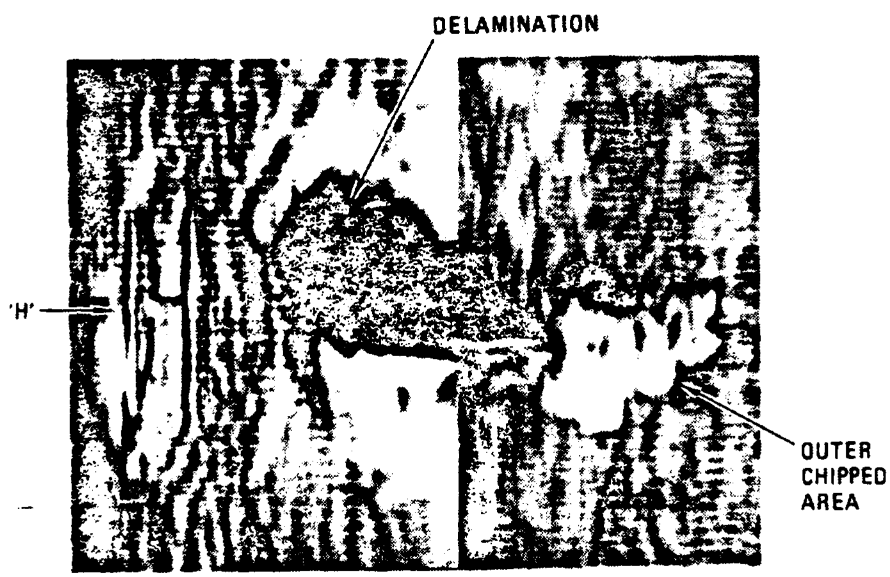

Figure 30. Frame Summed Ultrasonic Image of the 'H' Half Shell

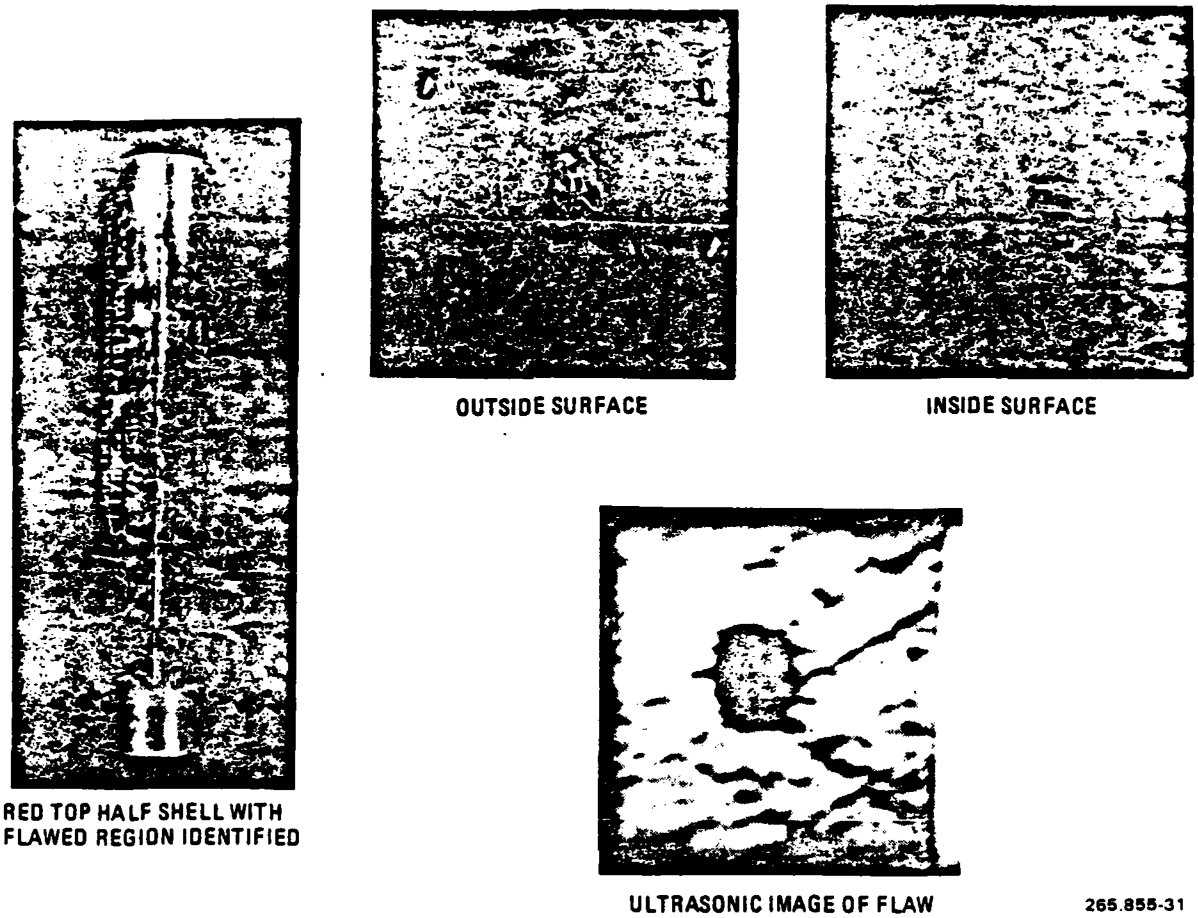

Figure 31. Ultrasonic Image (Slit Camera) of the Red Top Half Shell with Delamination

Red Top Half Shell

Delamination can be induced in fiberglass laminated material by hammer blows that leave little surface evidence of the extent of damage. Figure 31 shows a case in which minor surface evidence of damage exists on both the outside and the inside surfaces. The ultrasonic image more clearly shows the extent of the delamination.

Viper Launch Tube No. 531

A composite of four slit camera produced images is used in Figure 32 to show the full circumference of the tube. The vertical dimension of this strip is two inches. The major features in the picture moving from left to right are a rib structure with the image of a paper sticker to the right.

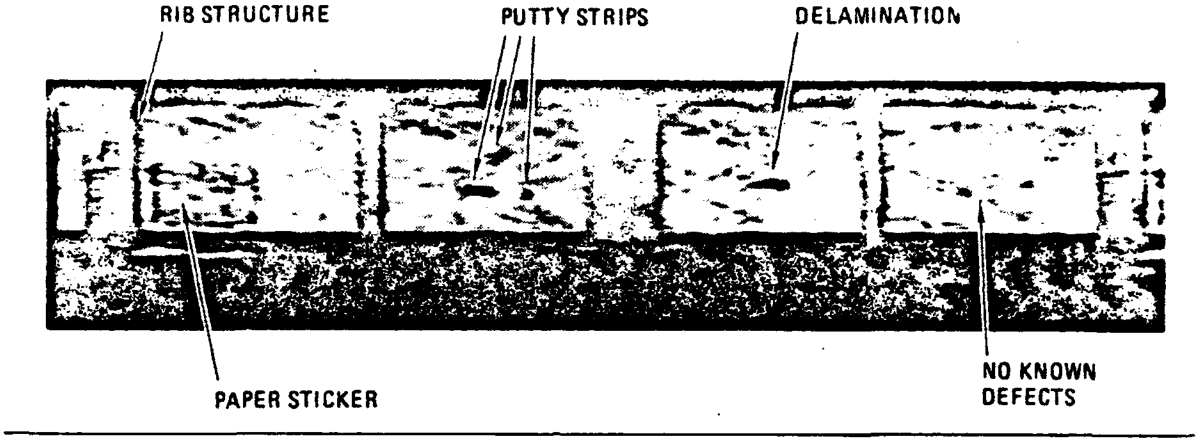

Figure 32. Viper Launch Tube No. 531

Following the paper sticker panel is a panel with three dark areas produced by putting one-eighth inch wide strips of putty on the outside surface. The smallest piece was about one-eighth inch square.

The third panel has a small delamination induced by a very light blow from a ball-peen hammer.

The fourth panel has no known defects and completes the circumference.

Aluminum Squeeze Casting

The squeeze casting shown in Figure 33 had several void volumes that were apparent upon visual inspection, but the full extent of the defect volume can only be seen in this ultrasonic image. The composite picture shown in Figure 33 distorts the height to width ratio due to splicing defects, but reveals extensive defects in the casting.

AREA MEASUREMENT

It is anticipated that in many cases defect decisions will be made on the basis of the area of the defect. A defect area will be identified as either a dark or a bright area in the field. Video image analyzing equipment can then be used to provide a signal proportional to the dark or bright area. Another feature of this video equipment allows the user to form a window within the object field. Only areas within the window will be integrated. These features are illustrated in Figure 34. A one-half inch thick nylon plate was built by pinning together three two-inch wide pieces of nylon plate. Two holes were drilled in the center piece. In the ultrasonic image, the two holes are dark and contrast strongly with the surrounding image. The video system detects the two holes as the darkest features in the field of view and identifies them as detected areas by

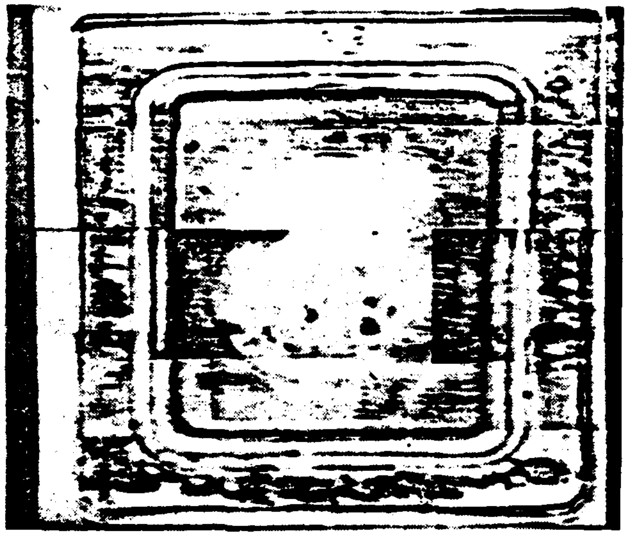

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Figure 33. Aluminum Squeeze Casting

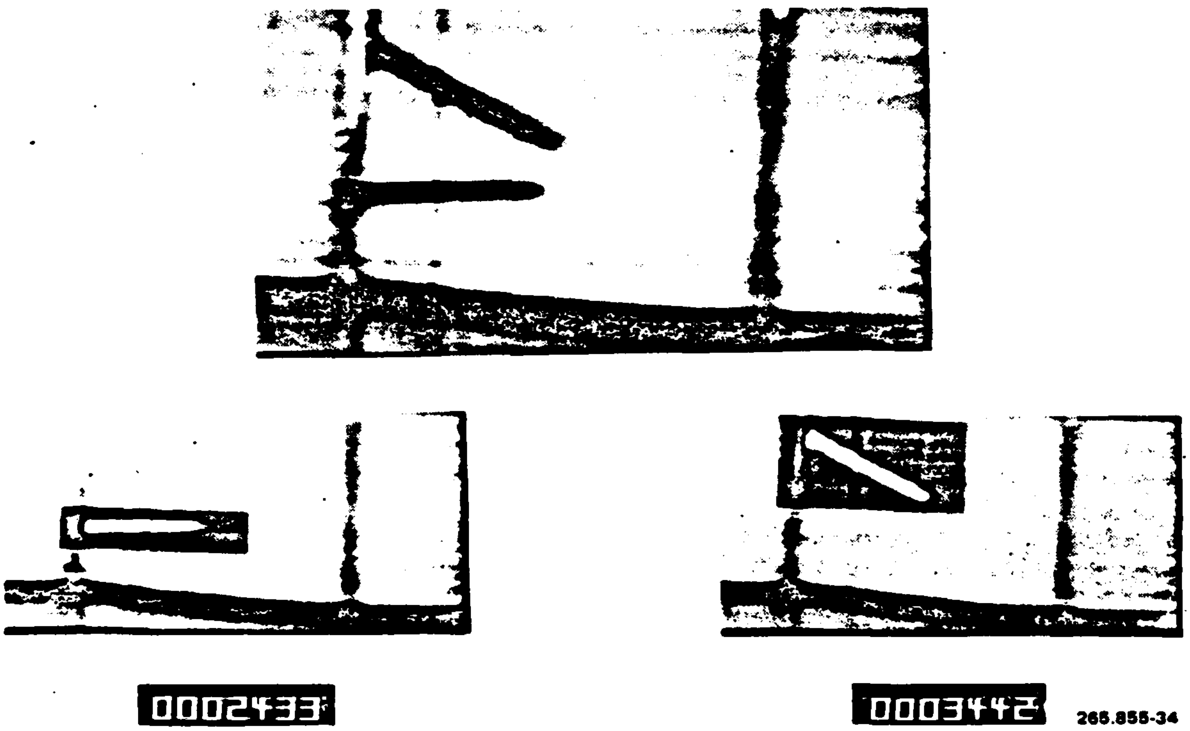

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Figure 34. Measurement of the Cross-Sectional Area of Drill Holes in a Nylon Plate

making them the brightest areas in the field. When a window is placed around the upper drill hole to exclude all other areas from measurement, the system counts 3,442 pixels in the detected area that corresponds to the upper drill hole. Similarly, when the window is placed around the lower (horizontal) drill hole, an area of 2,433 pixels is counted. At the magnification used for these images, each pixel corresponded to 4.17×10^{-5} square inches. The cross-sectional areas of the two holes are 0.143 in^2 and 0.101 in^2, respectively.

SECTION 4

CONCLUSIONS

The component requirements for a real-time ultrasonic imaging system (RTUIS) has been established. A breadboard system was assembled. Imaging of flaws was demonstrated using Viper launch tubes, Viper rocket motor casings, heavy austenitic steel weldments, and aluminum squeeze castings. Frame summing and averaging was shown to be effective for removing background patterns of ultrasonic transducers and speckle arising from the coherent nature of the ultrasonic wave. The usefulness of a scrolling digital memory was demonstrated by use of a special camera which generates a flat image of a cylindrical object. We are now in a position to proceed to Task II, the building, testing, and demonstration of the RTUIS prototype system.

SECTION 5

RECOMMENDATIONS

We recommend that the work of Task II begin as soon as possible in order to gain the economies of continuity of effort and in order to realize the benefits of 100% production run inspection as early as possible.

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